Mu2e, COMET & DeeMe: Experimental Searches for $\mu^{-}N \rightarrow e^{-}N$

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From Caltech (Mu2e)

Snowmass Rare Processes Frontier Town Hall Meeting

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Charged Lepton Flavor Violation (CLFV)

- The coherent, neutrinoless conversion of a muon to an electron in the presence of a nucleus ($\mu^- N \rightarrow e^- N$) is an example of Charged Lepton Flavor Violation.
- Highly suppressed in minimal extension to Standard Model. Rates far below any conceivable experiment could measure.

CLFV in the SM possible at loop level, but GIM suppressed.

$$BR(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$ [1-4]

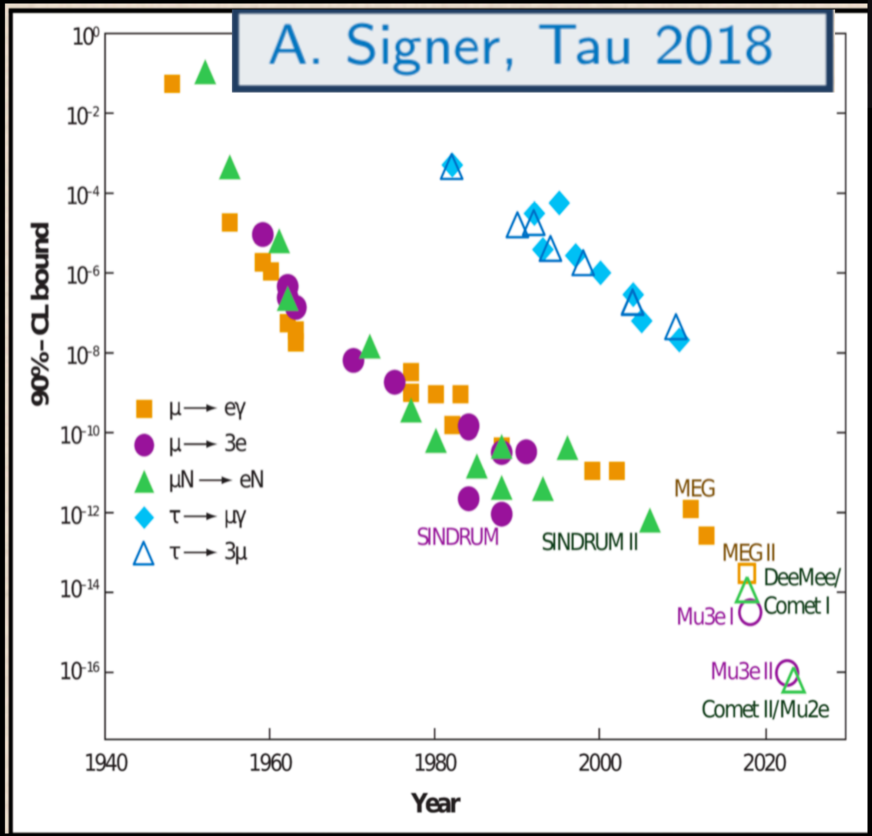
- Any signal in DeeMe, COMET or Mu2e would be an unambiguous signal of physics beyond the Standard Model (BSM).
- Broad array of BSM theories predict rates observable at these experiments - i.e rates 10^{-14} –10^{-17}

  → these experiments provide deep, indirect probes for new physics.

Experimental Searches for CLFV

- $\mu^{-}N \rightarrow e^{-}N$ searches are crucial part of global program searching for CLFV.
- To elucidate the mechanism responsible for any CLFV – must look at relative rates (if any) in different muon channels.

Mode	Current Limit (at 90% CL)	Future Proposed Limit	Future Experiment/s
$\mu^{\pm} \rightarrow e^{\pm}\gamma$	5.7 x 10^{-13} [5]	4 x 10^{-14}	MEG II[8]
$\mu^{-}N \rightarrow e^{-}N$	7 x 10^{-13} [6]	10^{-14}/10^{-15} / 10^{-17}	DeeMe[9]/COMET [10] Phase 1/ Mu2e[11], COMET Phase 2
$\mu^{+} \rightarrow e^{+}e^{+}e^{-}$	~10^{-12} [7]	10^{-15} ~ 10^{-16}	Mu3e[12]



$$R_{\mu e} = \frac{\Gamma(\mu^{-} + A(Z,N) \rightarrow e^{-} + A(Z,N))}{\Gamma(all - captures)} < 7 \times 10^{-13} (90\% C.L)$$

- Muon-to-electron sector provides powerful probes and complements collider searches for $\tau \rightarrow e\gamma$ or $\mu\gamma$ and $H \rightarrow e\tau,\ \mu\tau$, or μe.

Signal & Backgrounds

Signal:

- Monoenergetic electron $E_e = m_\mu - E_{recoil} - E_{1S\,B.E}$, e.g. 104.97 MeV in Al.
- Will be smeared by detector and stopping target effects.

Beam delivery systems optimized for high intensity, pure muon beam – must be “background free”:

Intrinsic physics background:

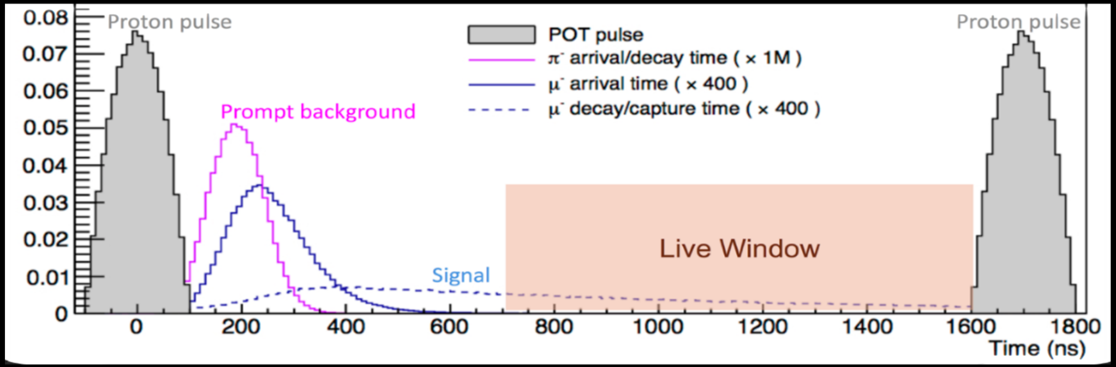
- Decay-in-orbit (DIO) - tail is 5-order polynomial near endpoint reaching to our signal region $\sim 105 MeV$ [13]
- Requires momentum resolution required to be better than $200\ KeV/c$

Beam related background:

- Pions - Mostly prompt. Can be suppressed by a delayed measurement window ($\sim$700 ns).
- Proton extinction factor required to be $< 10^{-10}$.

Cosmic ray background:

- COMET & Mu2e use active vetos around detectors.



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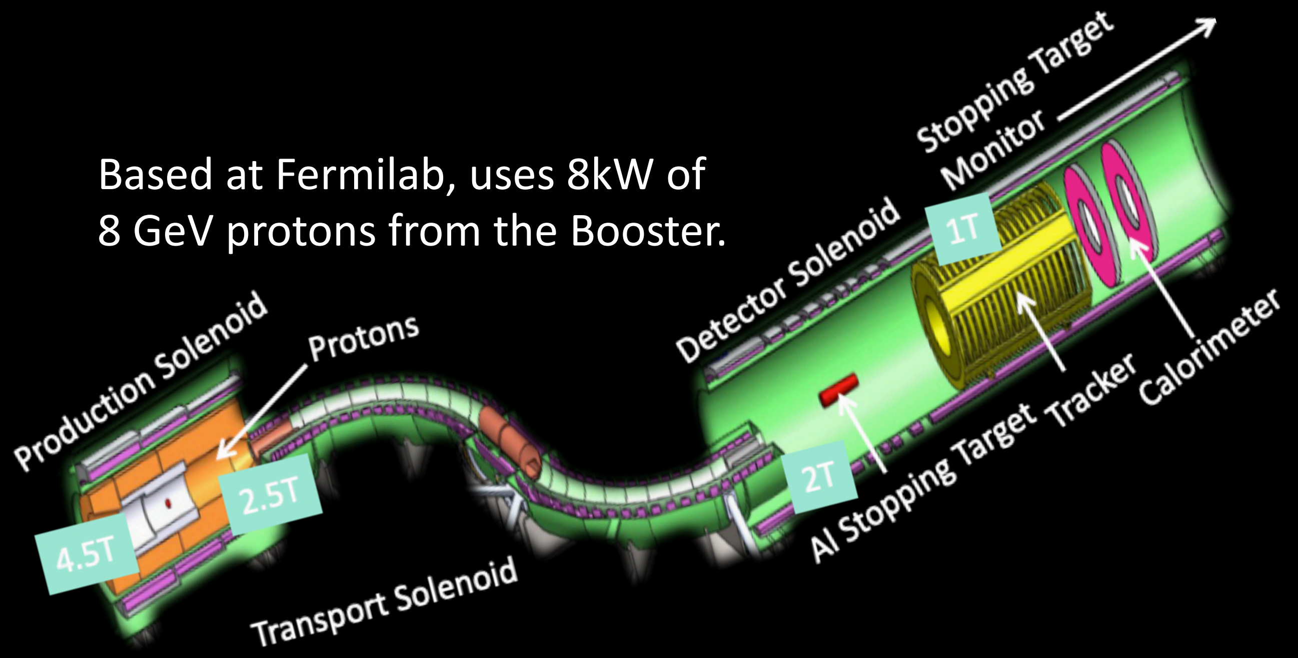
Mu2e: Design

- Mu2e & COMET based on MELC: V. Lobashev & R. Djilkibaev(Sov. J. Nucl. Phys. 49(2), 384 (1989)) .
- 3 Superconducting Solenoid Systems:
  - Production, Transport and Detector Solenoids.
  - Graded magnetic field.
- Low mass annular straw tube tracker:
  - > 20,000 straws;
  - wall thickness 15 μm;
  - provides momentum resolution of 180 KeV/c.
- 1348 CsI crystals in 2 annular rings provide complementary information and a fast trigger.
- Cosmic-Ray Veto (CRV) detects incident cosmic-ray muons.
  - Veto efficiency of 99.99% required.

Anticipated single-event sensitivity (SES): 3×10^{-17}

10^{4} improvement on Sindrum-II.

Based at Fermilab, uses 8kW of 8 GeV protons from the Booster.



Mu2e & Snowmass

Papers:

- Mu2e plan to submit 1 contributed paper – we are currently undertaking a large-scale simulation campaign which will provide updated estimates of our backgrounds and sensitivity. We will also have an updated run plan.

Collaborators:

- Snowmass & the Mu2e-II discussions have brought in collaborators from different backgrounds. We always welcome new collaborators!
- There are still many leadership roles for new collaborators: tracker, calibration, software etc.
- Installation and Commissioning is a great time for students to join.

Outcomes from Snowmass:

- Ensure continued support for full physics program. The physics goals of Mu2e are just as important as ever.
- Emphasize the importance Mu2e in the backdrop of the global CLFV.
- If any of COMET/Mu2e, MEG-II or Mu3e see a signal, all 3 channels must be measured to elucidate the cause.

Mu2e: Current Status

- Mu2e construction is nearly complete:
  - Beamline is finished.
  - Superconducting cable for all solenoids procured, winding for all three solenoid units is well-underway.
  - Transport Solenoid coils arrived at Fermilab, final testing and assembly underway.
  - Tracker straws, FEE prototypes, calorimeter crystals and SiPMs, STM detectors, and CRV counters are complete.
  - Assembly and testing of these detector components is on-going.
- Transition to installation in 2021;
- Detector commissioning beginning in 2022 ;
- Commissioning with beam continuing through 2023.
- Physics running is expected to begin in late 2023.

2020: Transport Solenoid at FNAL

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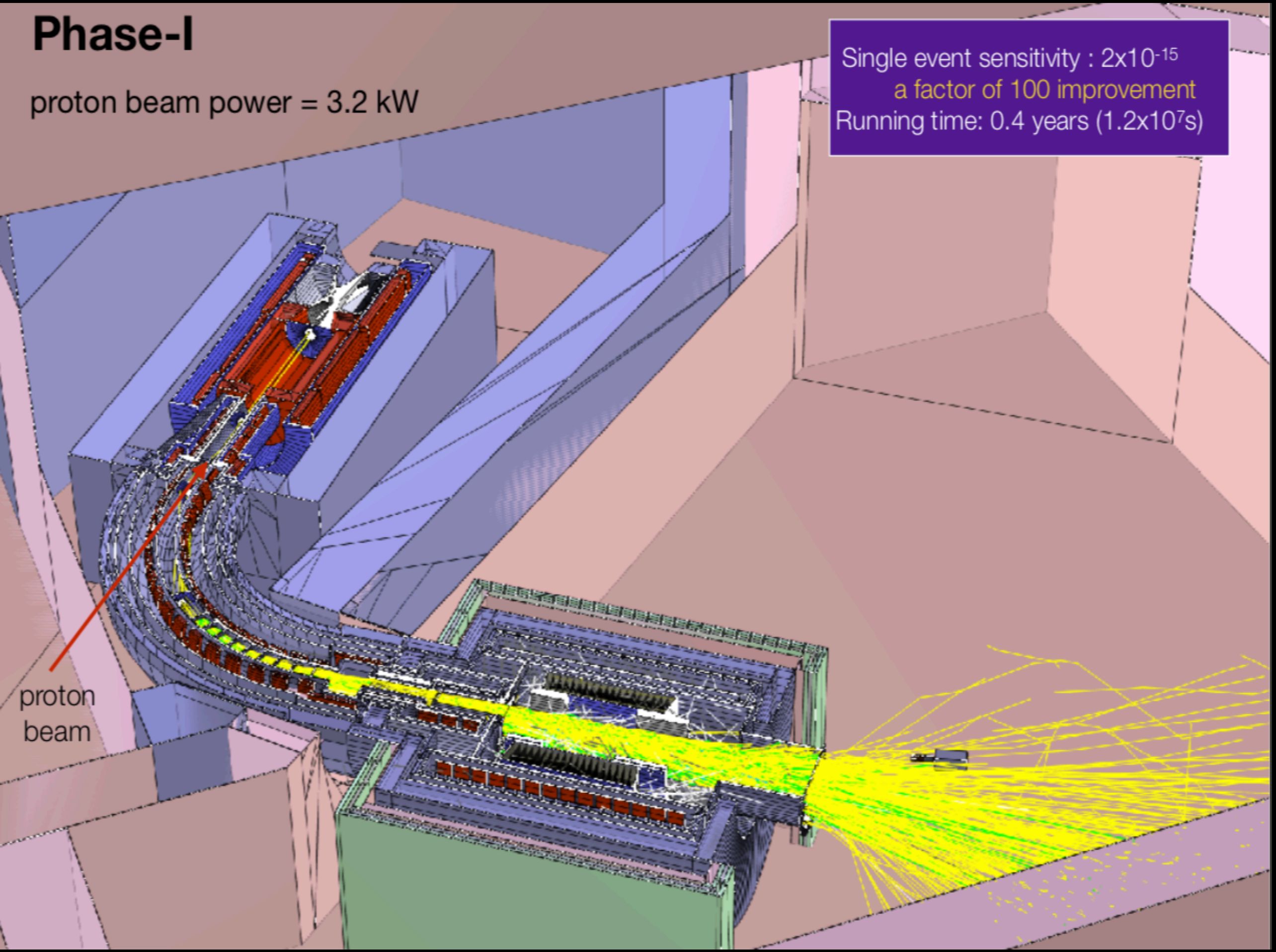
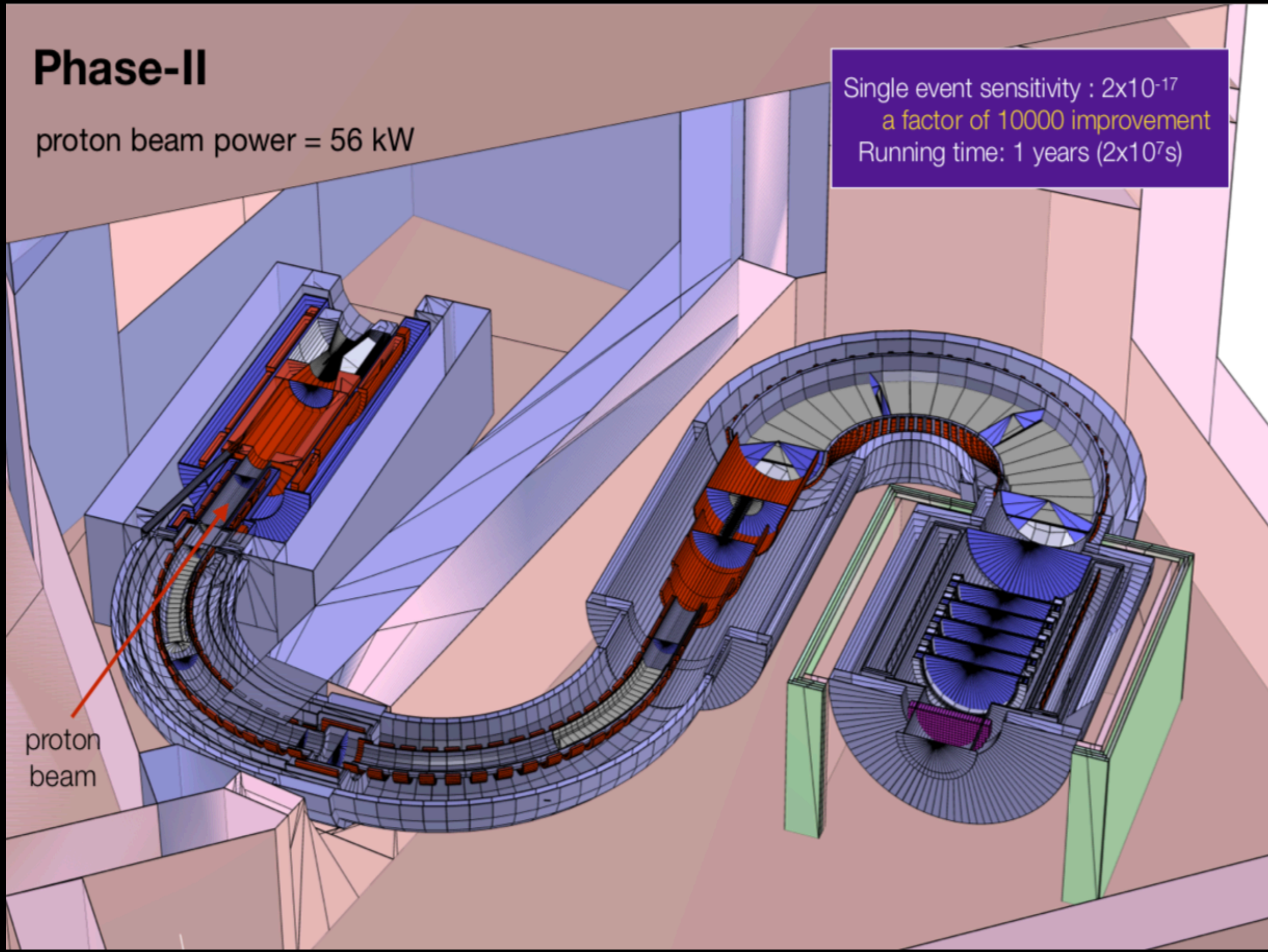
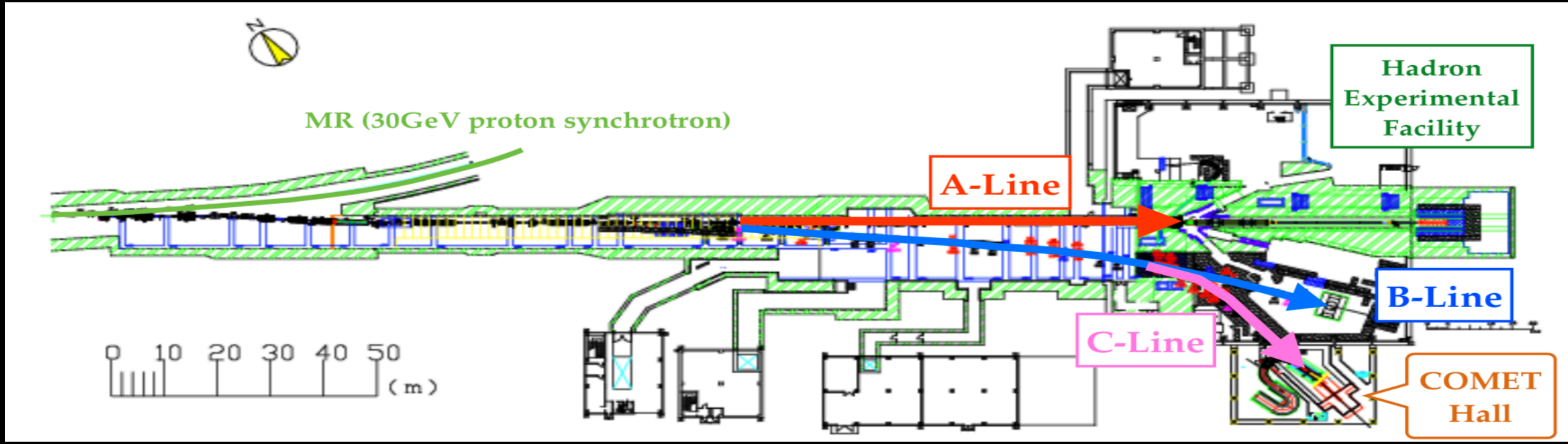
COMET: Phased Implementation



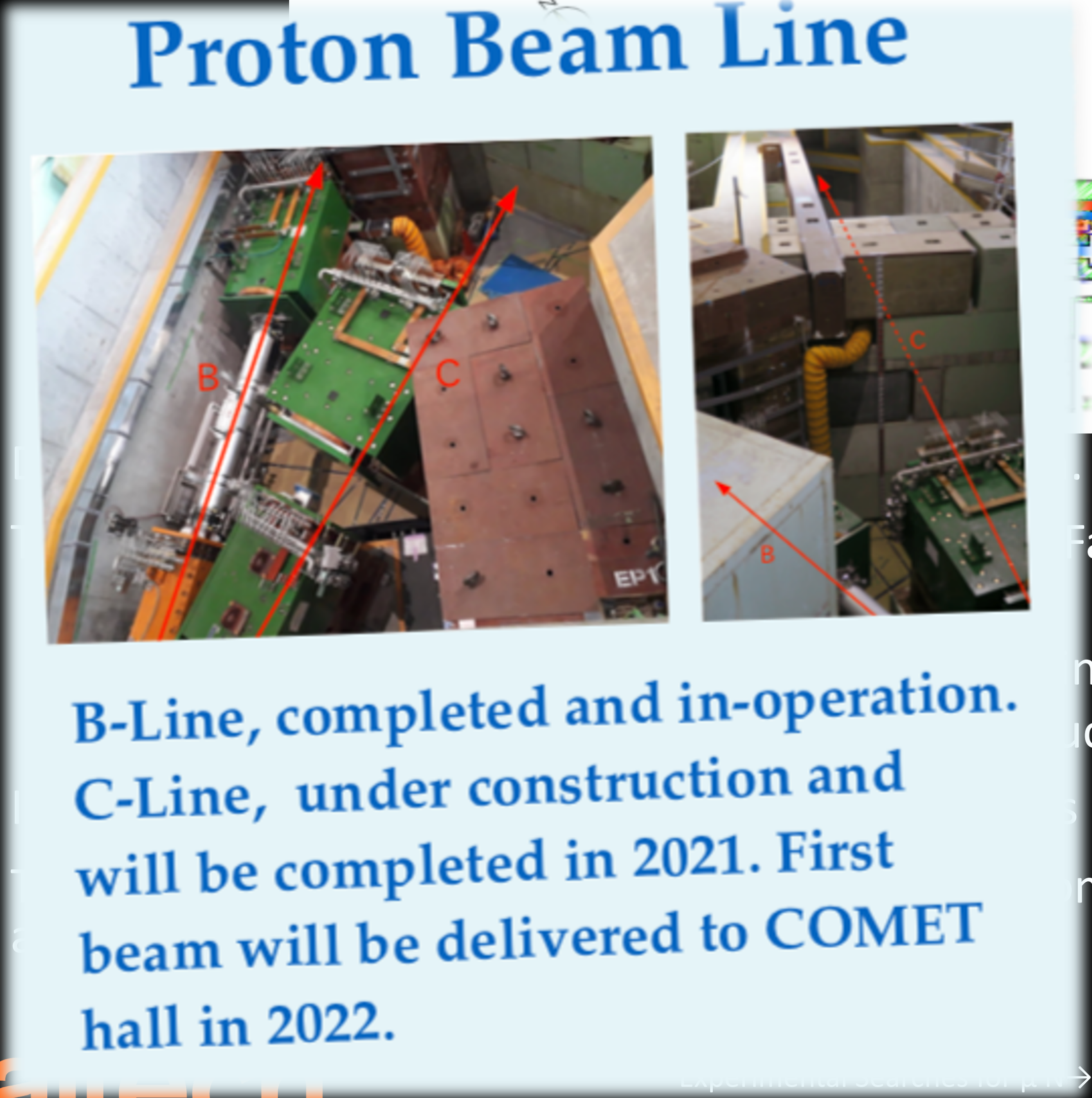


COMET: Facility Construction



- Dedicated proton beam line is under construction.
- Three proton beam lines in Hadron Experimental Facility:
  - **A-Line** in-operation.
  - **B-Line** completed and started operation in June 2020.
  - **C-Line**, dedicated for COMET, under construction and expected to be completed in 2021.
- Inside COMET hall, pion/muon transport system is under construction. All parts ready 2023.
- Transport solenoid is completed. Other components, pion capture solenoid, detector solenoid *etc.*, are under construction.

COMET: Facility Construction



- Facility
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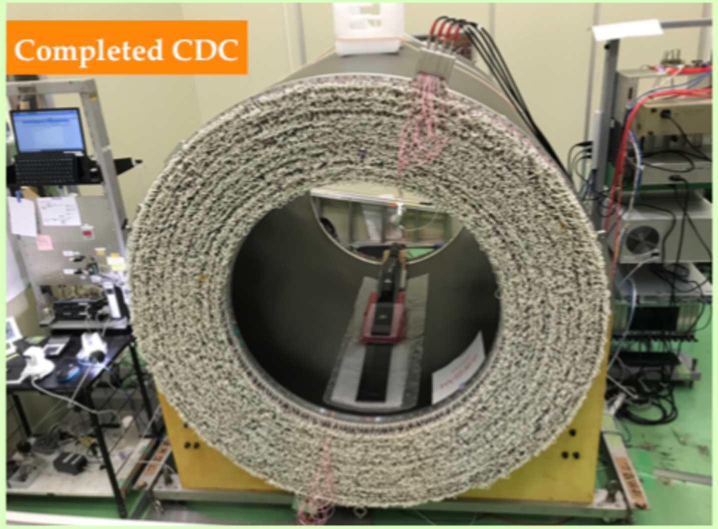
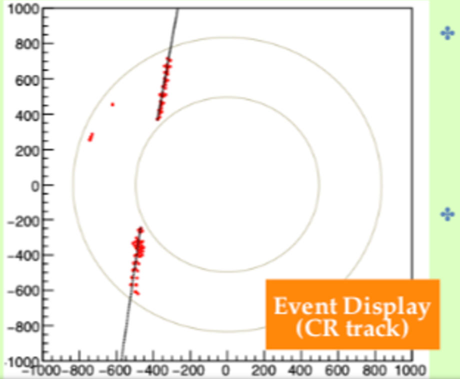
- uction
- unde
- mpon etc.,

COMET: Detector Construction

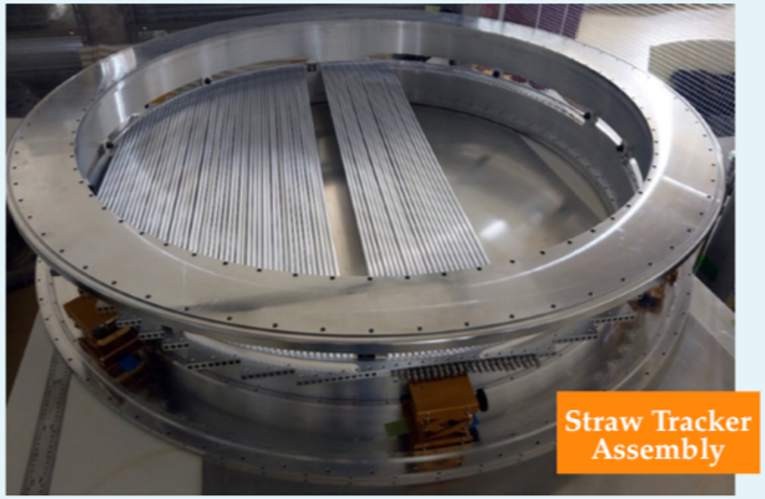
CyDet (for μ-e conv. search)



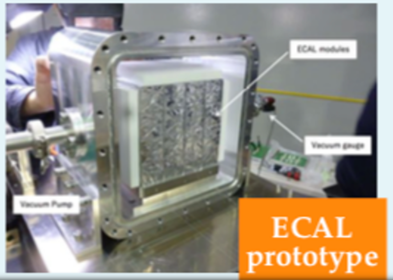


- CDC, completed and under commissioning with cosmic-ray.
- Trigger hodoscope is under development.

StrECAL (for beam measurement)



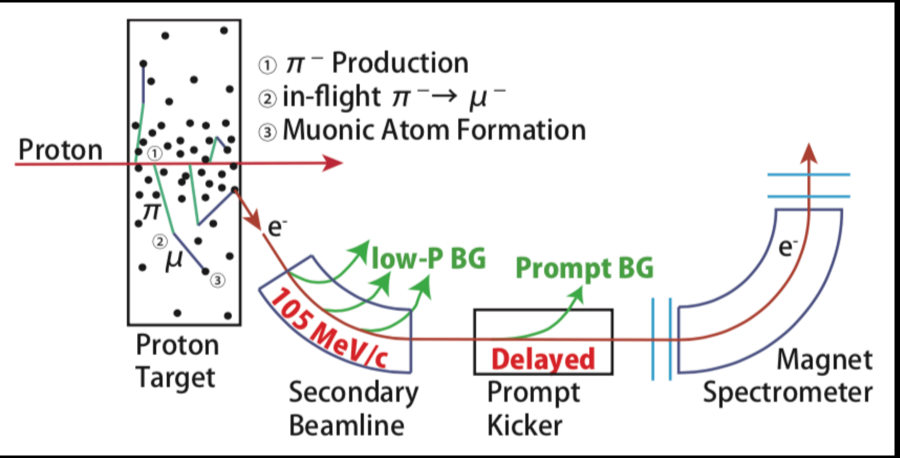
- Straw 1st station is under construction, will be completed soon.
- Five stations in total.

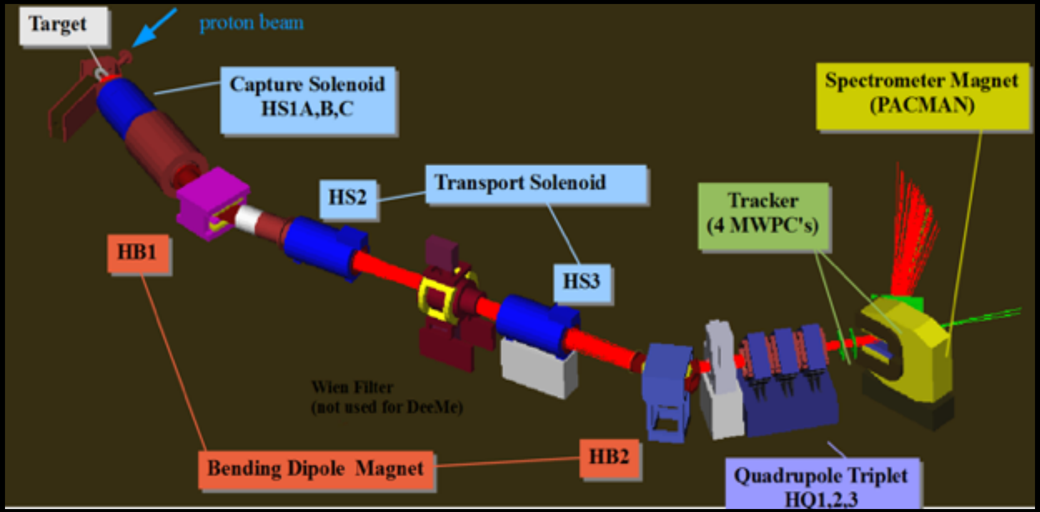


- ECAL prototype successfully completed.
- Detector assembly will start soon.

DeeMe

- Expected sensitivity of 1 x 10^{-13} (carbon) , 2×10^{-14}(SiC). 1 year, 1MW operation.
- Design – single production/stopping target:
  - Pulsed proton beams are injected into the target;
  - Target atoms and muons form muonic atoms.
  - Extract the decaying particles through the secondary beamline, H Line.
  - Magnetic spectrometer consists of a spectrometer electromagnet and four tracking detectors .
- The number of muonic atoms produced per proton-beam-power is 1/100 compared to Mu2e/COMET.
- Construction of detector system completed.
- Expect physics data following H-line completion in the next few years.





Summary

- Muon CLFV channels offer deep indirect probes into BSM.
- Mu2e, COMET and DeeMe at the forefront of active global CLFV program. They provide discovery potential over a wide range of well motivated BSM models.
- Muon-to-electron sector complements tau and Higgs collider searches such as: $\tau \rightarrow e\gamma$ or $\mu\gamma$ and $H \rightarrow e\tau, \mu\tau$, or μe.
- Expect limit on $\mu^{-}N \rightarrow e^{-}N$ to be improved by 4 orders of magnitude by the end of the decade (Mu2e/COMET Phase-II).
- These experiments will be indispensable pieces of the global search for new physics over the next decade, it is important they are supported throughout their physics programs to complete their physics goals.

Thank You for listening!

References

1. S. T. Petcov, Sov. J. Nucl. Phys. **25**, 340 (1977); Yad. Fiz. **25**, 1336 (1977) [erratum].
2. S. M. Bilenky, S. T. Petcov, and B. Pontecorvo, Phys. Lett. B **67**, 309 (1977).
3. W. J. Marciano and A. I. Sanda, Phys. Lett. B **67**, 303 (1977).
4. B. W. Lee, S. Pakvasa, R. E. Shrock, and H. Sugawara, Phys. Rev. Lett. **38**, 937 (1977); **38**, 1230 (1977) [erratum].
5. J. Adam *et al*. (EG Collaboration), Phys. Rev. Lett. **110**, 20 (2013).
6. W. Bertl *et al*. (SINDRUM-II Collaboration), Eur. Phys. J. **C47,** 337 (2006).
7. U. Bellgardt *et al*., (SINDRUM Collaboration), Nucl. Phys. **B299**, 1 (1988).
8. A.M. Baldini *et al*., “MEG Upgrade Proposal”, arXiv:1301.7225v2 [physics.ins- det].
9. DeeMe Proposal, submitted to KEK IMSS (2010).
10. Y. Kuno *et al*., “COMET Proposal” (2007)
11. Mu2e TDR, arXiv:1501.05241
12. Nuclear Physics B - Proceedings Supplements Volumes 248–250, March–May 2014, Pages 35-4
13. A. Czarnecki et al., “Muon decay in orbit: Spectrum of high-energy electrons,” Phys. Rev. D 84 (Jul, 2011) .
14. Sindrum-II “Improved limit of Branching Fraction of mu- →e+ in Titanium”, Phys Lett B 422 (1998) 334-338 (1998)

Relevant LOIs

1. COMET -https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-100.pdf
2. DeeMe - https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-097.pdf
3. Mu2e - https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_SophieMiddleton-025.pdf
4. Mu2e-II - https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0_Frank_Porter-106.pdf

Complementary Searches

$\mu^{-}N \rightarrow e^{+}N$

- This conversion violates both lepton number ($\Delta L = 2$) and lepton flavor conservation, and can only proceed if neutrinos are Majorana particles.
- The Mu2e/COMET sensitivity to $\mu^- \rightarrow e^+$ extends beyond the current best limit [14]
- $< m_{e\mu} >$ effective Majorana neutrino mass scale sensitivity down to the MeV region, surpassing the $< m_{\mu\mu} >$ sensitivity in the kaon sector which is limited to the GeV region

$\mu^{-}N \rightarrow eXN$

- Where X is a new light boson (or axion).
- Feasibility under study.

Physics Reach

Estimate sensitivity CLFV process in model independent manner by adding 2 different LFV effective operators to the SM Lagrangian:

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\Big(\sum_{q=u,d}\bar{q}_L\gamma_\mu q_L\Big)$$

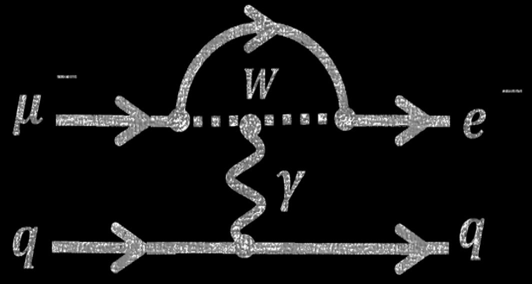
κ<<1

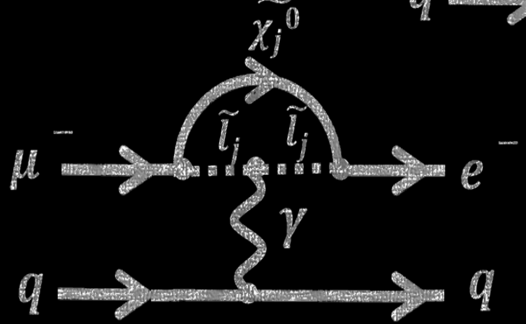
"Photonic"

$\mu^\pm \rightarrow e^\pm\gamma$, $\mu \rightarrow eee$

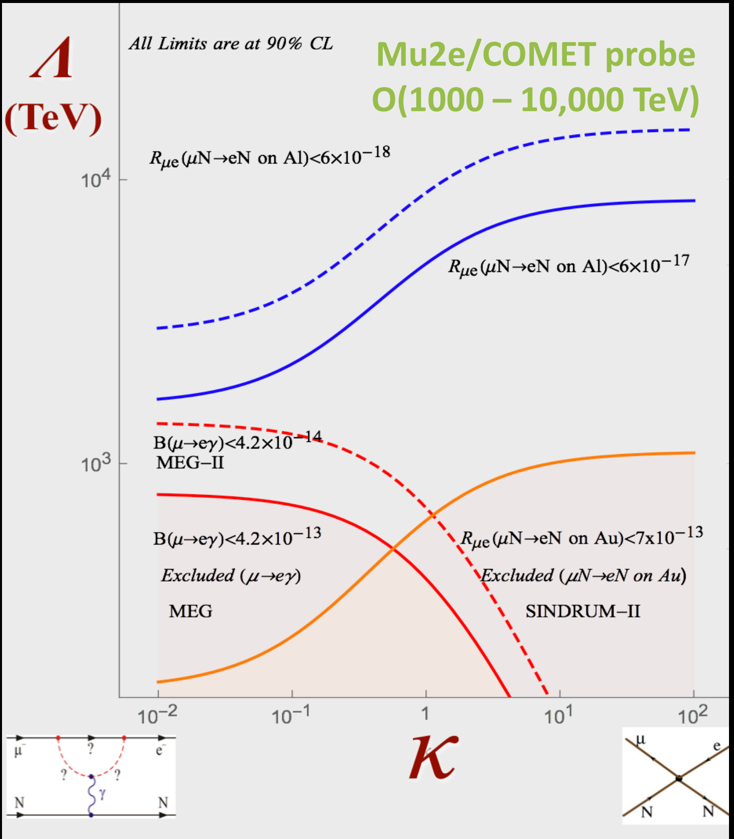
$\mu^- N \rightarrow e^- N$

Heavy Neutrinos





SUSY



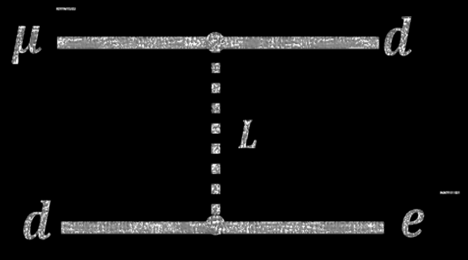
κ>>1

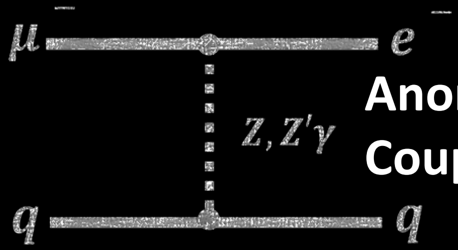
"Contact"

Only $\mu^+ \rightarrow e^+e^+e^-$

And $\mu^- N \rightarrow e^- N$

Leptoquarks





Anomalous Couplings

λ = the effective mass scale of NP,

κ = controls the relative contribution of the two terms

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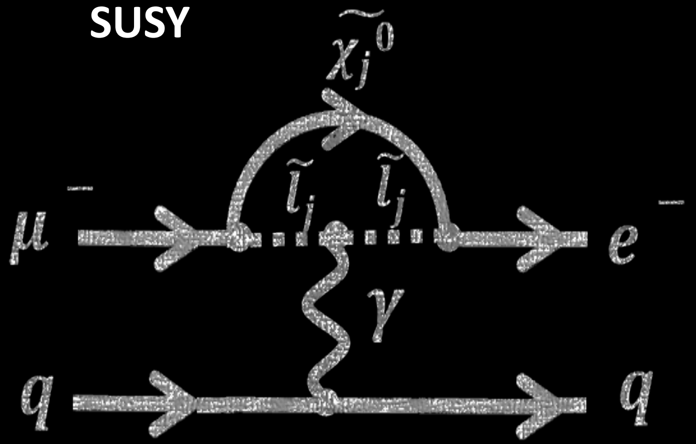
Physics Reach

Theory Reviews: Y. Kuno, Y. Okada, 2001; M. Raidal et al., 2008
A. de Gouvêa, P. Vogel, 2013

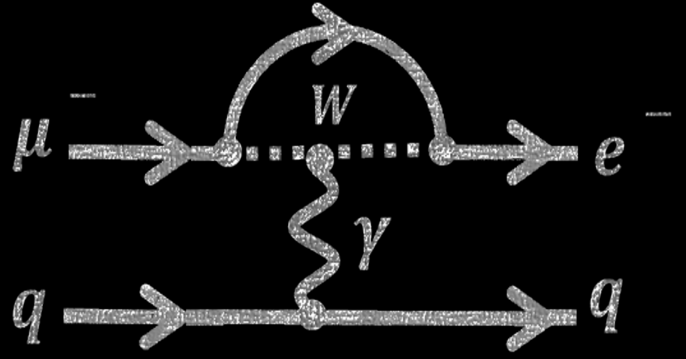
Multitude of possible new physics contributions to $\mu N \rightarrow eN$ which predict $R_{\mu e}$ $O(10^{-15})$ or higher:

Loop "Photonic"

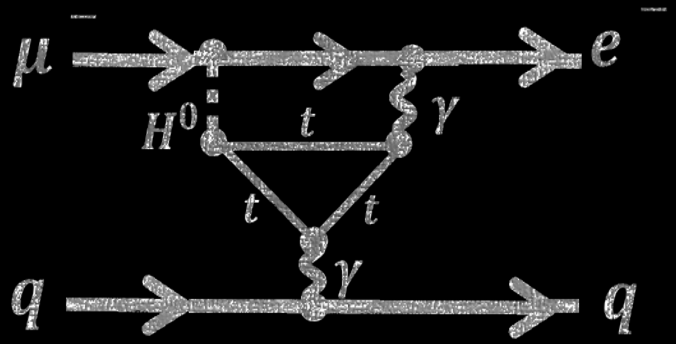
SUSY



Heavy Neutrinos

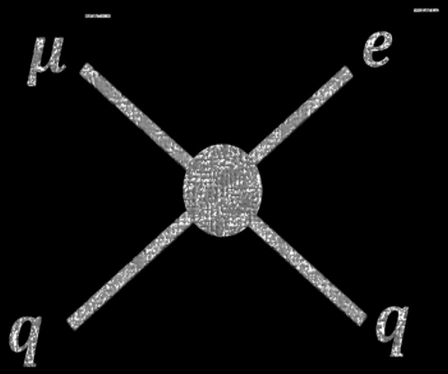


2 Higgs Doublets

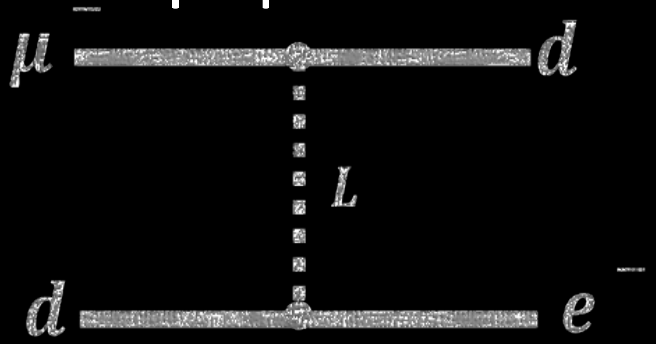


"Contact"

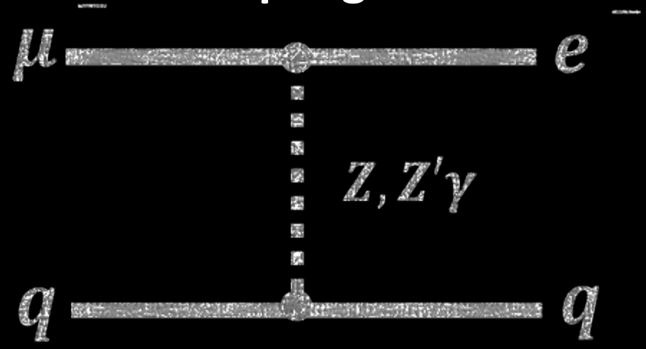
Compositeness



Leptoquarks



Anomalous Couplings



Discovery Sensitivity

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★

★★★ = Discovery Sensitivity

Discovery sensitivity across the board. Relative Rates however will be model dependent.

*arXiv:0909.1333[hep-ph]

What happens if we see a signal?

V. Cirigliano, S. Davidson, YK, Phys. Lett. B 771 (2017) 242
S. Davidson, YK, A. Saporta, Eur. Phys. J. C78 (2018) 109

If we do see a signal in Al:

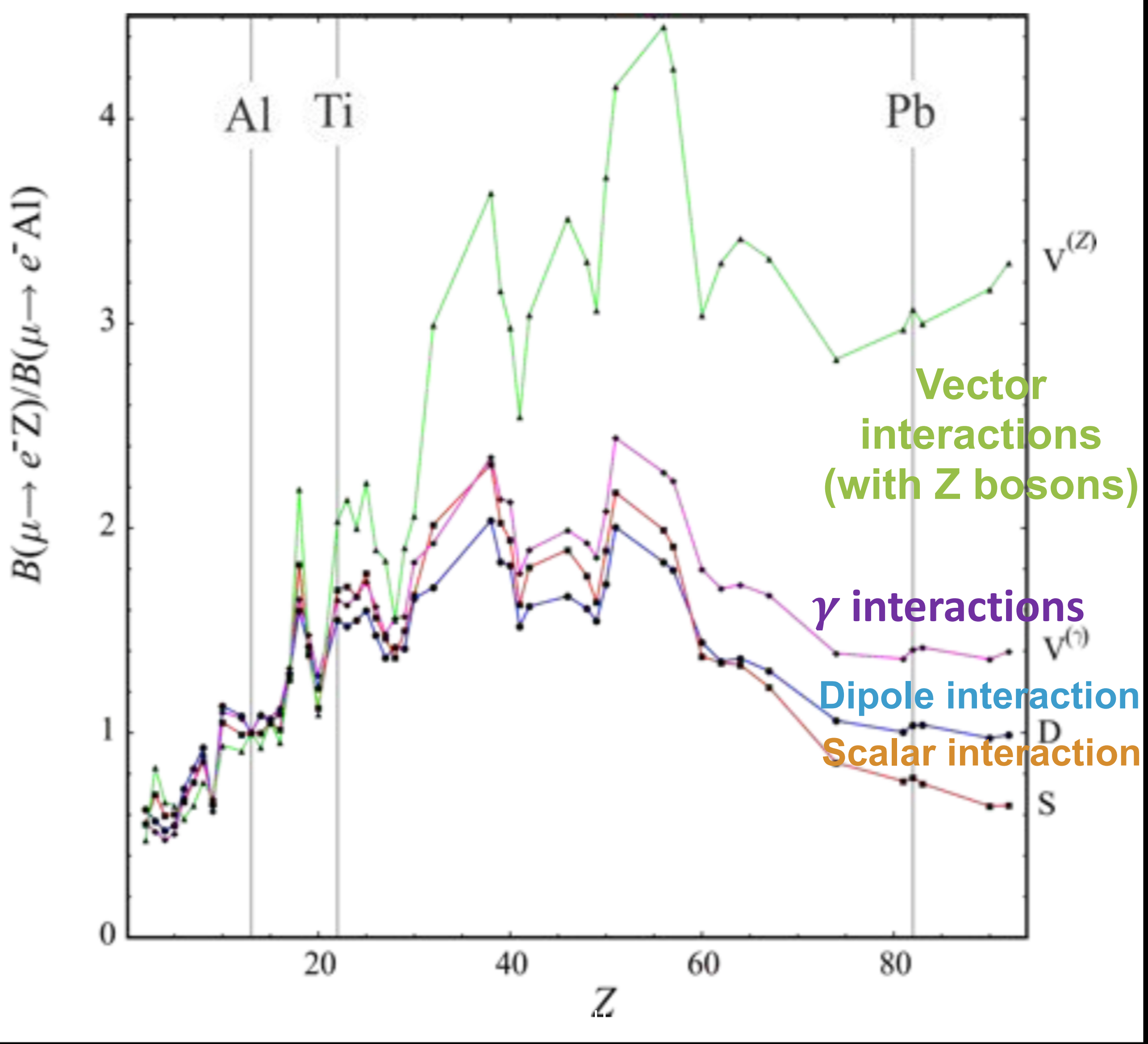
- Various operator coefficients add coherently in the amplitude.
- Weighted by nucleus-dependent functions.

➔ Requires measurements of R in other target materials!

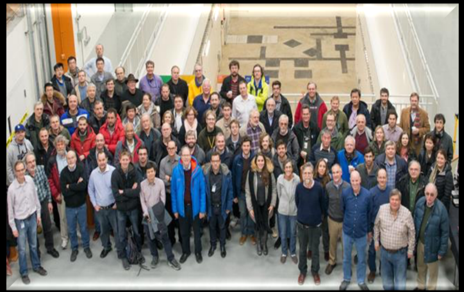
	S	D	V^1	V^2
$\frac{B(\mu\to e,\mathrm{Ti})}{B(\mu\to e,\mathrm{Al})}$	$1.70 \pm 0.005_y$	1.55	1.65	2.0
$\frac{B(\mu\to e,\mathrm{Pb})}{B(\mu\to e,\mathrm{Al})}$	$0.69 \pm 0.02_{\rho_n}$	1.04	1.41	$2.67 \pm 0.06_{\rho_n}$

y = nuclear scalar form factor, ρ_n = nuclear neutron density

5% measurement on Al/Ti needed to see split



Mu2e: Status

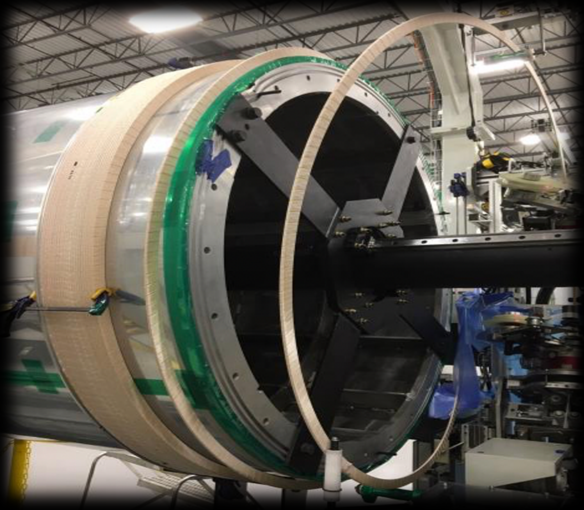


Mu2e Building complete

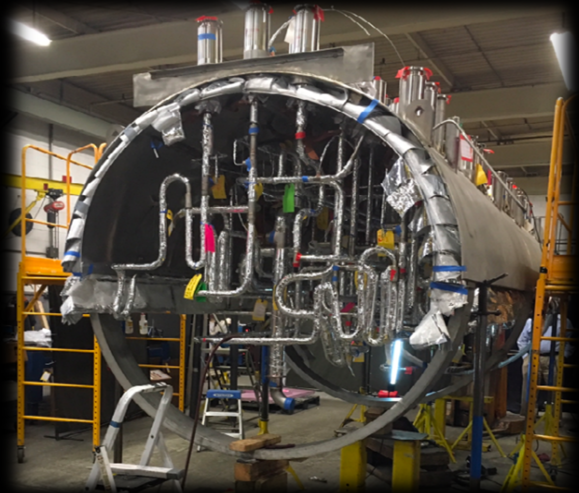
2020: All Calorimeter Crystals delivered and tested. Assembly beginning.

2019: Warm bore and thermal shield procurement completed.

2020: Transport Solenoid assembled and tested at FNAL



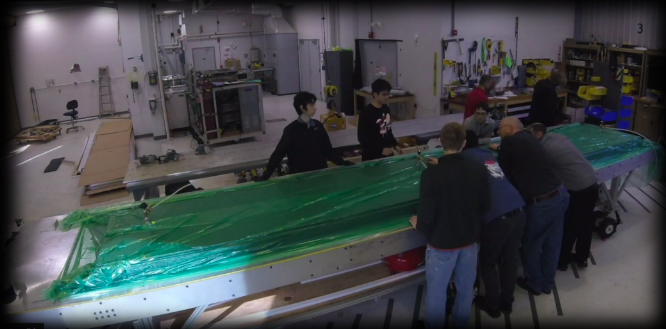
Winding of DS and PS well underway.



2019: Cryogenic Distribution Box constructed

Straw Tracker construction ongoing

Cosmic Ray Veto Assembly on going



2019: Completed transfer lines

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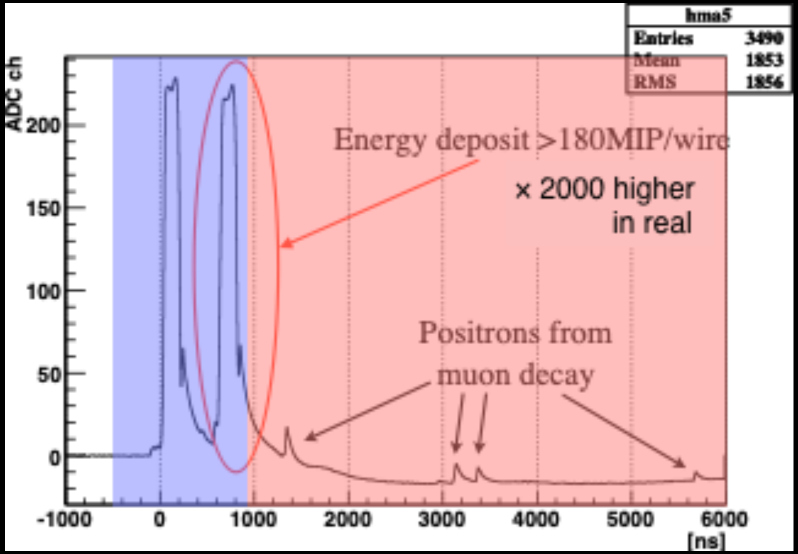
DeeMe Collaboration

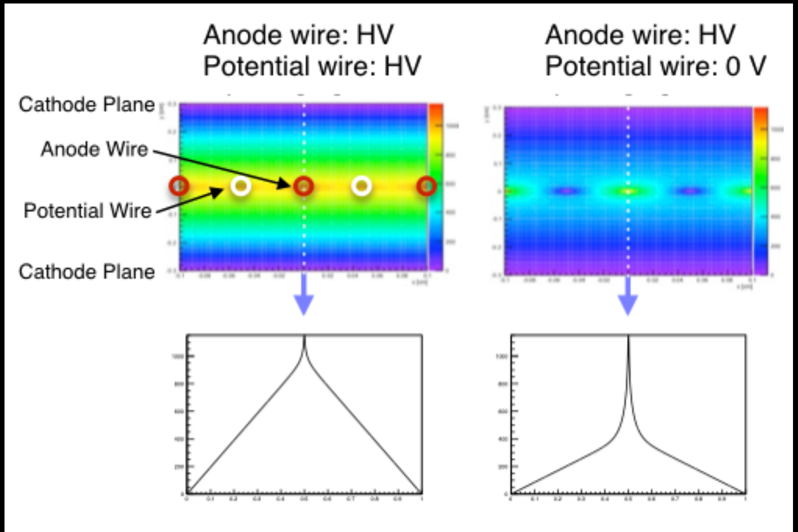
M. Aoki[1], D. Bryman[2], H. Ikeuchi[3], Y. Irie [4],
S. Ito[9], N. Kawamura[5], M. Kinsho[6], H. Kobayashi[4],
K. Komukai[3], S. Makimura[7], H. Matsumoto[4], S. Meigo [6],
S. Mihara[7], Y. Miyake[7], D. Nagao[1], Y. Nakatsugawa[14],
H. Natori[5], H. Nishiguchi[7], T. Numao[8], C. Ohomori[4],
S. Ritt[10], P.K. Saha[6], N. Saito[7], Y. Seiya[3], K. Shigaki[11],
K. Shimomura[5], P. Strasser[5], T. Takahashi[3], N. Teshima[3],
N.D. Thong [12], N.M. Truong [13], K. Yamamoto[6], K. Yamamoto[3],
T. Yamazaki[5], M. Yoshii[4]

(1) Osaka University, (2) UBC, (3) Osaka City University,
(4) KEK Accelerator, (5) KEK MUSE, (6) JAEA, (7) KEK IPNS, (8) TRIUMF,
(9) Okayama University, (10) PSI, (11) Hiroshima U.,
(12) U. of Science Vietnam National U. Ho Chi Minh City,
(13) UC Davis, (14) IHEP

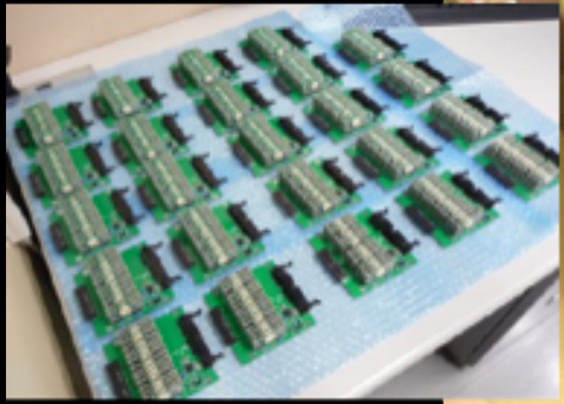
Spectrometer R & D Completed:
Prog Theo Exp Phys 2017 023C01

DeeMe: HV-switching MWPC





Preamps @ 2015



FADC

Magnet
borrowed from TRIUMF

DeeMe: Integration Test & DIO Measurement

- Integration test of the system:
  - MWPC×4 + Amp. + FADC + DAQ
  - Used yet-another smaller magnet.
- Measurement of DIO spectrum in mid. mom.
  - target: C, Si and SiC
- 2017/3 — 2 days: 2016B0277
- 2017/6 — 5 days: 2017A0267
- **The whole system worked very well**
  - no MWPC breakdown at all.
  - DAQ efficiency ~ 100%
- **High-Statistics run: 6 days in 2019/3.**
  - as a general-type program: 2019B0315
  - better MWPC performance
  - **Successfully accumulated more events.**